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Modeling and Simulation of Series DC Motors in Electric Car

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Abstract

The objective of this paper is assessing use of series DC motor in electric car with its rotation speed controller, and evaluating its performances when different running cases of electric car with different loads.
The mathematical equations model of series DC motor and electronic inverter in dynamic state with reference frame d – q were considered.
Computer model of these equations was implemented using MATLAB/SIMPOWER facilities obtaining a complete model for motor and controller. Series DC motor is considered and its parameters were used for simulation. The electronic controller operates based on PWM control technique.
Simulation of series DC motor performances was conducted within presumptions of changing car load and different resistant torques.
Changing loads was realised changing number of passengers when electric car is running on normal streets, when running on streets with slope, when car is accelerate to reach a stead speed and when car is changing speed rigidly and suddenly running on country road having some holes and small slopes.
Some conclusions and remarks about performances and behaviour of series DC motor were concluded. The simulated series DC motor was tested and mounted experimentally in a small truck car in Faculty of Mechanical & Electrical Engineering at Damascus University.

Selection and peer-review under responsibility of the Euro-Mediterranean Institute for Sustainable Development (EUMISD)

Key words: Series DC motor; Simulation; PWM inverter; Electric Car.

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1. Introduction:

The manufacturers of cars in cooperation with scientific research institutions and technical universities jointly conduct research for the development of several types of electric motors especially for use in automotive applications. As a result there were several types of electric motors chosen for use in vehicles, such as DC Motors, Induction Motors and Variable Magnetic Resistance motors. That most commonly used and currently the most prevalent are the three-phase inductive motor followed by the series DC motor. [7]
In this research a series DC motor used in electric traction in general and for electric cars in particular, will be considered. The operating equations of such motors and equivalent electric circuit will be modelled and simulated using MATLAB/SIMULINK. A suitable switched Electronic controller based on PWM technique is used to drive this motor and control its speed; this controller was modelled in the same complete computer model. Simulation of motor and inverter was carried using this complete model. The results are evaluated and commented in order to implement this series DC motor on a small truck car at Faculty of Mechanical & Electrical Engineering in Damascus University, converting it into an electric car. The study of the motor performances was conducted within presumptions of changing car load from one passenger (the driver) to 6 passengers, as well as motor performance when electric car is running with different load torques on variable roads slope and when car is running on rural roads.

2. Mathematical model of series DC motor:

DC Motors are considered the best type of motor from the point of speed control and regulation its speed with high accuracy and fine increments. A practical case study on the control of a series DC motor designed for traction applications was applied on motor having the following electrical specifications:

Nominal Voltage:	Un = 48Vdc	Nominal Current:	In = 218A
Nominal Power:	Pn =10.5KW	Nominal Rotation speed:	Vn = 2850 rpm

The advantage of using this type of motor is the possibility of changing the direction of rotation by reversing the polarity of the input Voltage. This motor also has a high torque that is proportional to the Square value of the load current. Fig. 1 shows the equivalent circuit for the series DC motor.

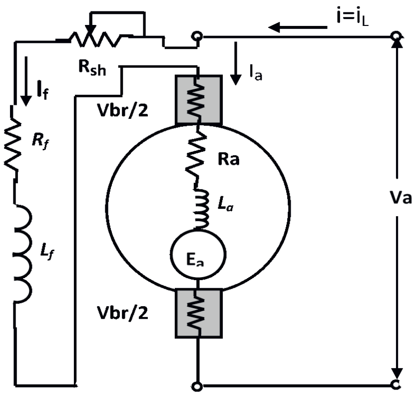

Fig. 1Electric circuit of series DC motor

The following running equations of series DC motor were used to establish the computer model for simulation of series DC motor: [4] [6].
The equations related to the operation of the series DC motor representing the mathematical model, are as follows:

- Electromotive force in dynamic state:

$$E_a = K_a.\phi.\omega_m \qquad\qquad E_a = K_a.\phi.n$$

- Voltage equation in dynamic state:

$$U_a = e + i_a(R_a + R) + (L_a + L_f).\frac{di}{dt} + U_b$$

- Voltage equation in steady state:

$$U_a = E + R_a.I_a + U_{br}$$

$$E = U - (R_a + R_f).I_a - U_{br} = K_a.\phi.n$$

- Power equations:

$$P_e = \omega_m.Tem = r_a.i_a \quad \text{Or} \quad U_a.i_a = E.i_a + R_a.I_a^2 + U_{br}$$

- Electromagnetic toque equations:

$$Tem = \frac{P_b}{\omega_m} \quad \text{Or} \quad Tem = K_b.i_a$$

- Motion or torques equation:

$$Tem - Tmech = T_a = j.\frac{d\omega_m}{dt} + b_1.\omega_m$$

Assuming that the value of the voltage drop across the collector and brushes is very small to a point where they can be neglected or that the DC motor is brushless then:

$$n = \frac{U - (R_a + R_s)I_a}{C_e \cdot \phi}$$

$$n = \frac{U - (R_a + R_s)I_a}{C_e \cdot \alpha \cdot Ia} = \frac{U}{C_e \cdot \alpha \cdot I_a} - \frac{(R_a + R_s)}{C_e \cdot \alpha}$$

This equation characterizes the speed as a function of current N=*f (n)* according relation of the form n=K-K'
Were as constant K and constant K' are defined as follows:

$$K' = \frac{(R_a + R_s)}{C_e \cdot \alpha} \qquad\qquad K = \frac{U}{C_e \cdot \alpha \cdot I_a}$$

The total load torque is resulting from resistant torques of the car and weight of car with driver and passengers this resulting torques are inertia torque of the car, dynamic torque of the air (air friction resistance), slope torque (torque generate by inclining roads) and torque required overcoming the friction of the car tires with the road.

3. Simulating the series DC motor and the inverter:

According to mathematical model of dynamic state for the series DC motor mentioned above, the following model has been developed using MATLAB/SIMULINK tools and shown in fig. 2.
The control system that was used operates in a closed loop configuration providing a stable output during changes in the operating parameters of the system. This is achieved by sampling the output of this system and comparing it with a desired values constantly giving feedback of errors in output values to PID controller for processing. The control systems used in continuous PID controllers are commonly used to address the error signal based on the desired parameters such as speed, torque, current and position to adjust the values of these parameters so as to achieve better transient response through several criteria, including the relative deviation of the output such as speed, control the speed of response, static error and the oscillating of the system.

The common way to start addressing problems related to the speed of response is through the proportional part of the controller, while processing errors occurring in the steady-state is in the integral amplifier part; whereas the differential part has the complementary role in damping oscillations occurring in a transient state while reaching the desired state. The pedal based control used to drive a DC motor in electric car is done based on PWM (Pulse Width Modulation) technique, which is one of the modern methods in the control of motors which offers lower power loss during control of motor. [5]

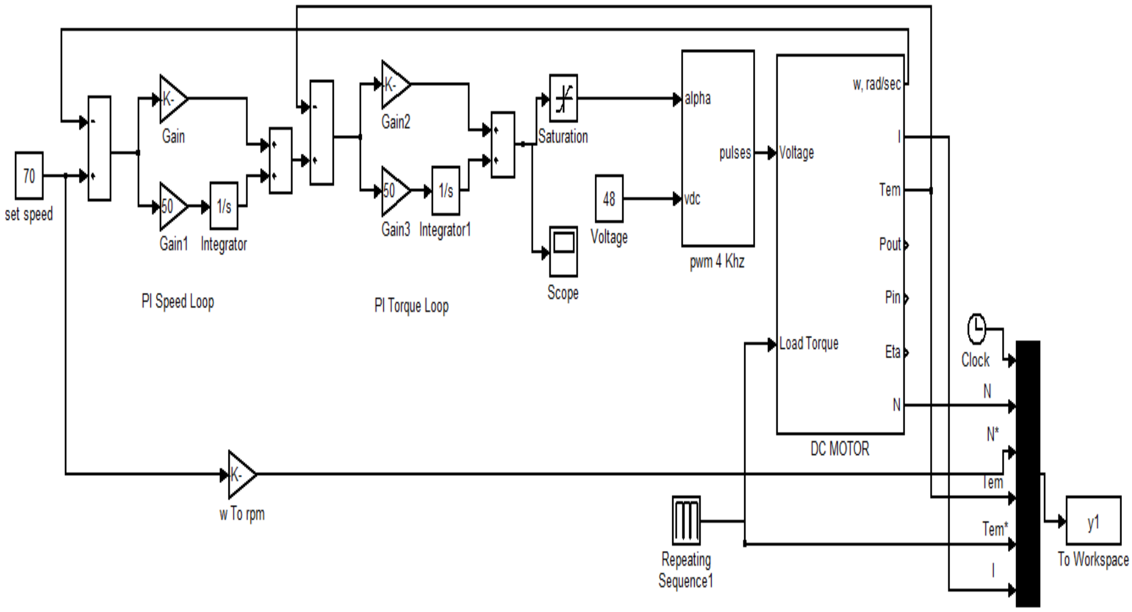

Fig. 2 Simulation model of series DC motor with inverter

The technique is based on feeding the motor a square wave with variable width pulses applied to IGBT transistors which are at the core of the power output stage of the controller.
Considering that Kp, Ki, Kd are constants of the PID (proportional - integral - differential) respectively and e (t) as a continuous error signal that represents the difference between the measured value (current) and the value of the desired (reference) to measure rotation speed of the motor as function transfer (position - Voltage) and (speed - voltage) as follows:[2] [3]
The function of position-voltage:

$$\frac{\theta}{V}=\frac{K}{S((J.S+B).(L.S+R)+K^2)}=\frac{K}{L.JS^3+(LB+RJ).S^2+(R.B+K^2).S}$$

The function of speed-voltage:

$$\frac{\theta'}{V}=\frac{w}{V}=\frac{K}{(J.S+B).(L.S+R)+K^2}=\frac{K}{L.JS^2+(LB+RJ).S+(R.B+K^2)}$$

This equation has been simulated in MATLAB as shown in figure 3.

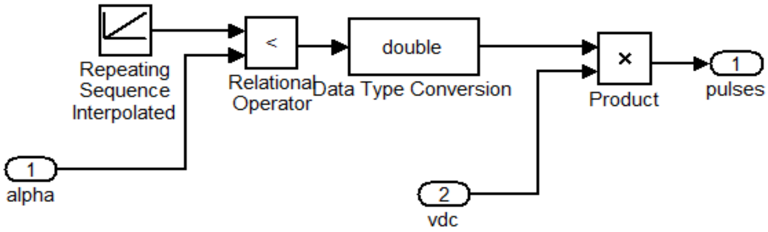

Fig. 3 Simulation model of inverter

4. Simulation results:

The series DC motor was tested with inverter using simulation of the complete model implemented in MATLAB/SIMULINK to study its behaviour if used in electric car. The tests were conducted in several proposals in which the electric car was considered running in different cases. These cases can simulate the running with different loads on motor axis while car is moving from 0 rpm speed and accelerating till steady speed is reached and maintained for a period of time; running on streets with slopes applying smooth increase to speed; running on rural roads having holes and small slopes which force the driver to break and change speed.
A series DC motor with parameters shown in table. 1 was simulated and the following tests were carried using the computer model of the series DC motor and its controller given in fig. 2.
This series DC motor was tested in laboratory and was used on a small truck to change it in electric car. Fig.4

Fig. 4 The realised electric car

Table. 1

Vn = 48 V	R = Ra + Rf = 0.1 Ohm	Ke = 0.004	B = 0.05 N.m/ra.s^{-1}
L= La+Lf=0.005 H	KT = 0.0036	J = 1 Kg.m^2	

It must be mentioned that series DC motor can't run without load, so as the car is stopped and motor will be out of supply and its speed is 0. Changing rotation speed is done by accelerating pedal changing motors current.

3.1. Simulation the running of Series DC Motor applying different load torques, considering the weight of empty car is 550 kg, the weight of driver and 5 passengers which is 450 kg.
In fig. 5 are given variation in time of torque, current and rotation speed of the Series DC motor when a load torque equal to 100% of the nominal torque of DC motor is applied.

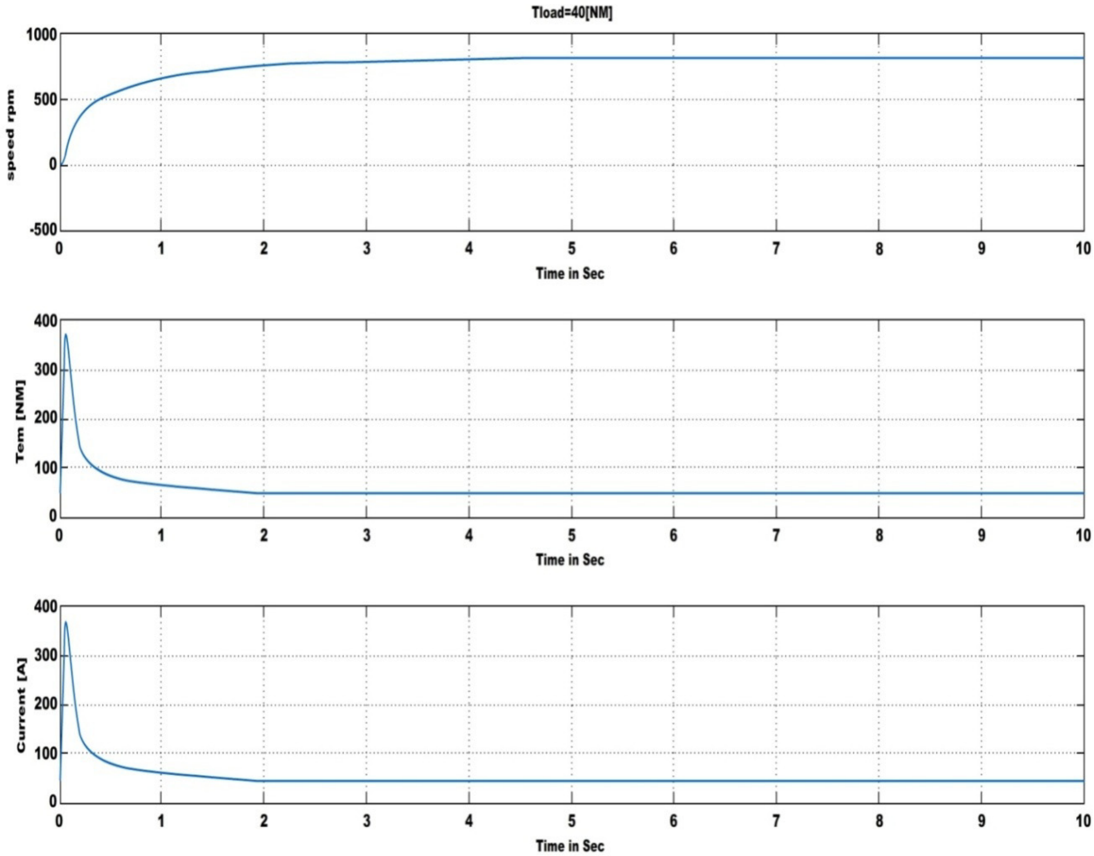

Fig. 5 Variation in time of rotation speed, torque and current of motor
When a load torque equal to 100% of nominal torque is applied

Fig. 5 shows the simulation results of series DC motor operating with load torque of 100% of nominal torque is applied on axis of motor, rotation speed, torque and current varying in time are given. The value of starting active torque in this case reaching 360 N.m which is about 9 time nominal torque, but it last for less than o.2 sec. and can be sported easily by series DC motor. After a transient period of 2 sec. the active torque value became stable and equal to nominal value. The fig. shows also that rotating speed is varying smoothly from 0 to 570 rpm and remains stable. Starting current reach a value of 370 A and after transient period it became stable and equal 45 A.
In Fig.6 are given variation in time of rotation speed, torque and current of the Series DC motor when a load torque

equal to 70% of the nominal torque of DC motor is applied.
Fig. 6 shows the same for applied load torque of 70% of nominal torque. The value of starting active torque in this case reaching 350 N.m which is about 9 time nominal torque, but it last for less than o.2 sec. and can be sported easily by series DC motor. After a transient period of 2 sec. the active torque value became stable and equal to nominal value.
Fig. 6 also shows that rotating speed is varying smoothly from 0 to 1000 rpm and remains stable. Starting current reach 350 A and after transient period it became stable and equal 40 A.
In Fig.7 are given variation in time of rotation speed, torque and current of the Series DC motor when a load torque equal to 15% of the nominal torque of DC motor is applied.

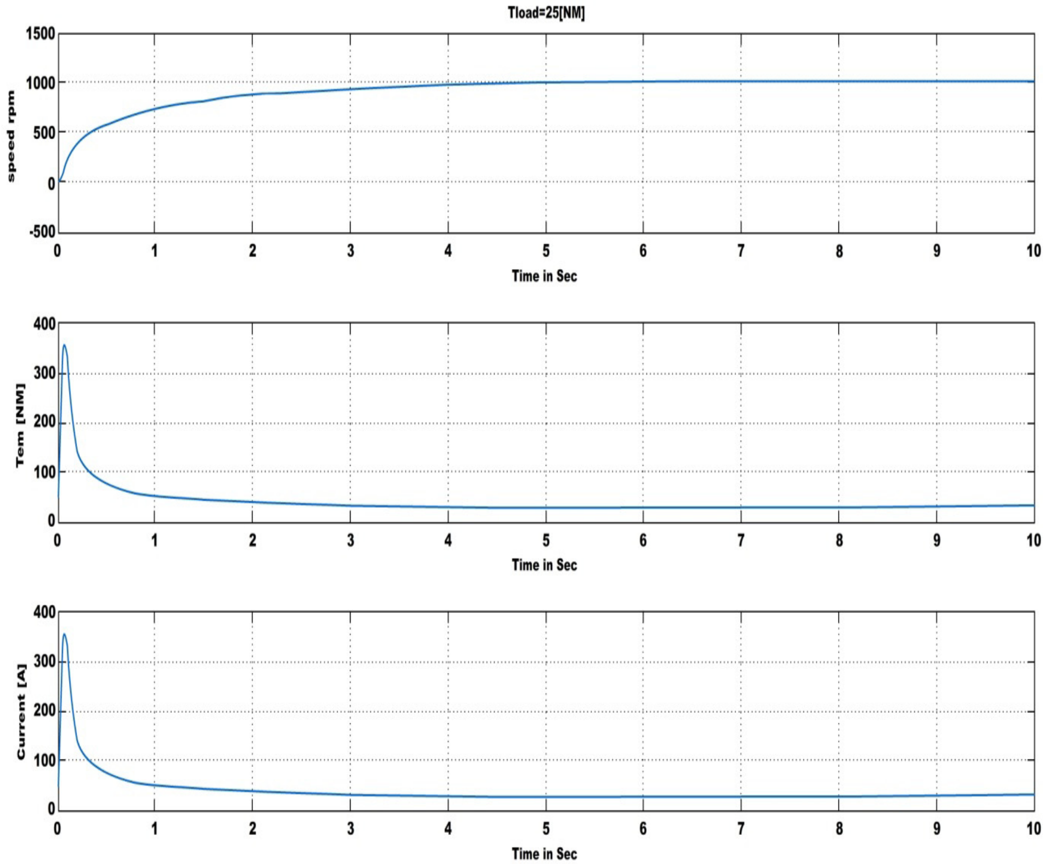

Fig.6 Variation in time of rotation speed, torque and current of motor
when a load torque equal to 70% of nominal torque is applied

Fig. 7 shows the same for applied load torque of 15% of nominal torque. The value of starting torque in this case reaching 320 N.m which is about 8 time nominal torque, but it last for less than o.2 sec. and can be sported easily series DC motor. After a transient period 2 sec. the active torque value became stable and equal to nominal value. Fig. shows also that rotating speed is varying smoothly from 0 to 1500 rpm and remains stable. Starting current reach value of 320 A and after transient period it became stable and equal 35 A.
These results show that tested series DC motor is very suitable insuring necessary active torque needed for electric car traction having different loads.

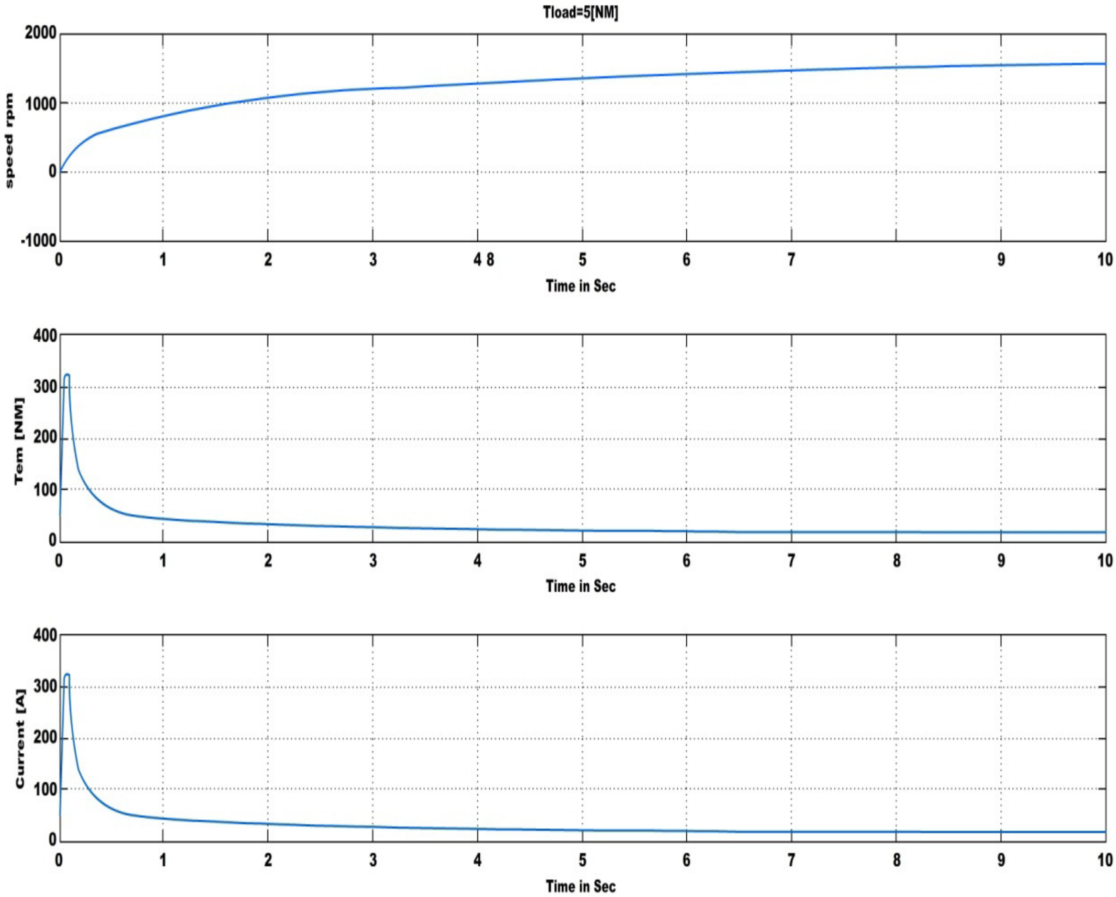

Fig 7 Variation in time of rotation speed, torque and current of motor when a load torque equal to 15% of nominal torque is applied.

3.2. Simulation the running of series DC motor applying different load torques, when the car is moving on constant acceleration to reach steady speed fixed by driver.

In fig. 8 is given variation in time of torque and rotation speed of Series DC motor when a load torque equal to100% of the nominal torque of DC motor is applied.

Fig. 8 and Fig. 9 show simulation results of series DC motor when a constant acceleration is applied to increase rotation speed from 0 rpm (car is stopped) to reach steady speed fixed by driver. Acceleration is applied by accelerating pedal in car.

Figs. also show role of controller to keep rotation speed equal to preset speed. The value of starting torque in Fig. 8 reached 350 N.m which is about 10 times the value of active torque and reached 275 N.m which is about 8 times the value of active torque. These values are in admissible limits of DC motor characteristics. The transient time for acting torque and rotation became stable is 2 sec.

3.3. Simulation the running on country roads having holes and small slopes which force driver to change speed and to use break. In fig. 10 are given variation in time of torque and rotation speed of series DC motor in this case when a load torque equal to100% of the nominal torque is applied

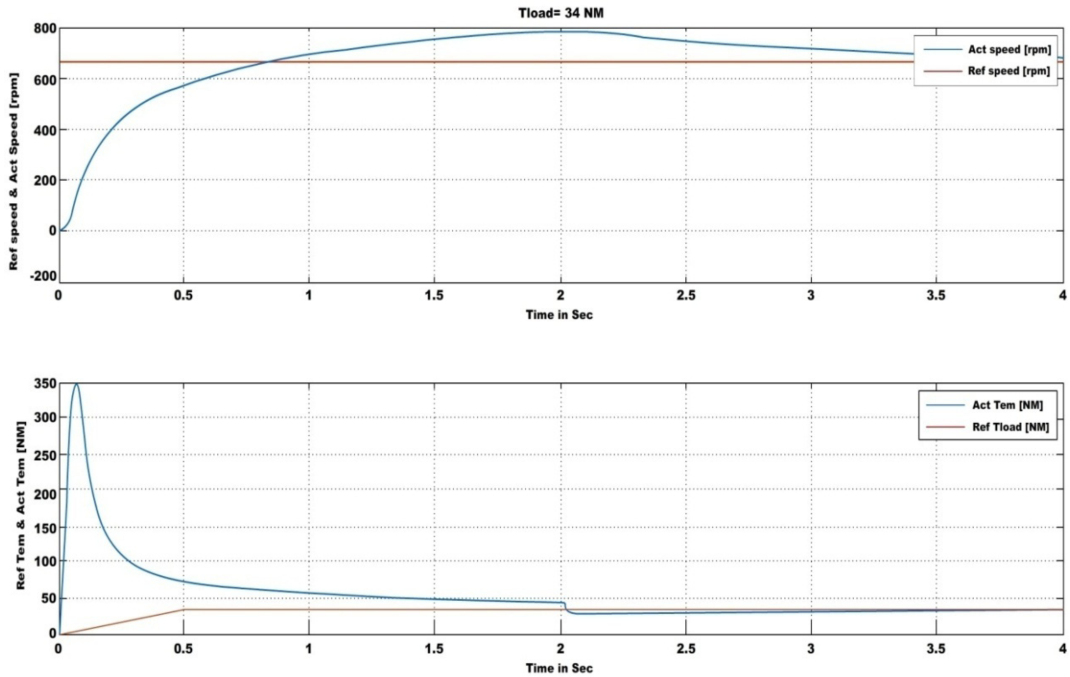

Fig. 8 Variation in time of rotation speed and torque of motor for 100% load torque car moving with acceleration to reach steady speed

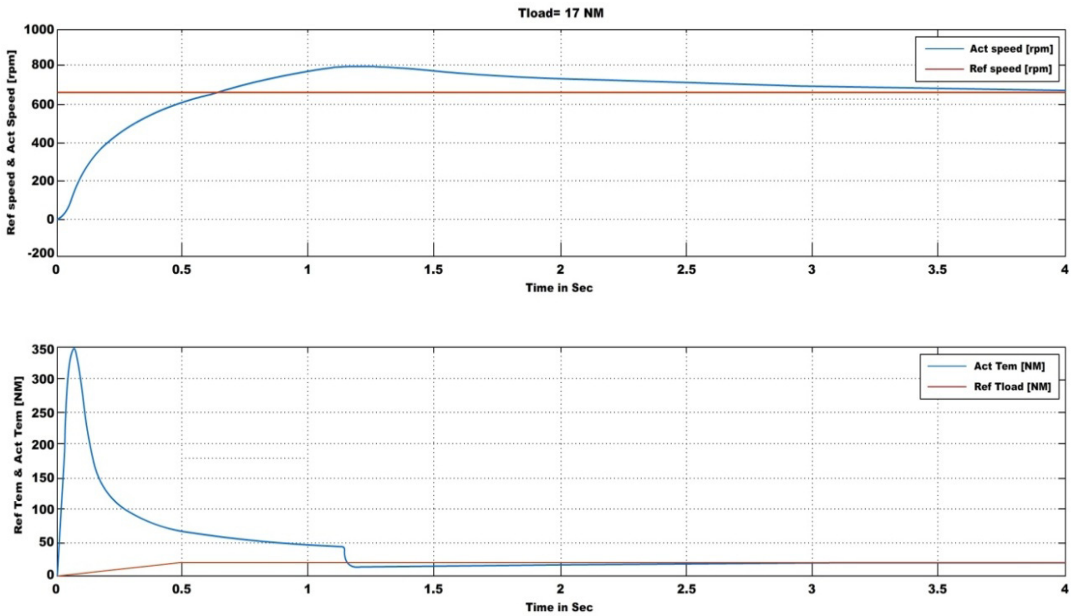

Fig. 9 Variation in time of rotation speed and torque of motor for 50% load torque car moving with acceleration to reach steady speed

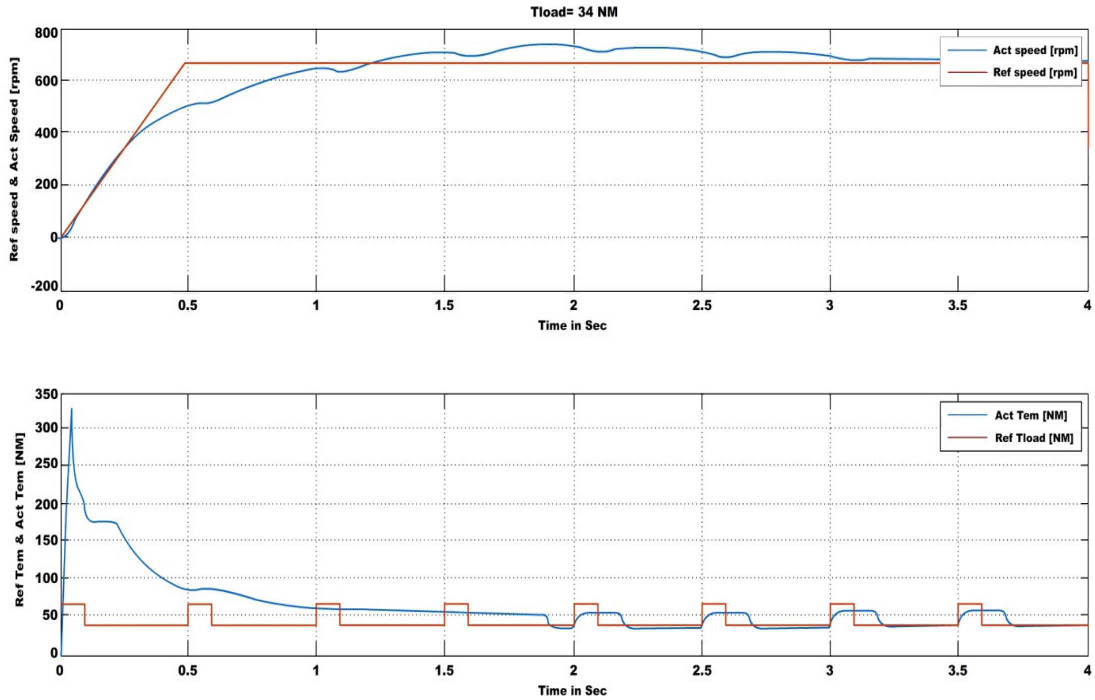

Fig. 10 Variation in time of rotation speed and torque of motor for 100% load torque when car moving on country road

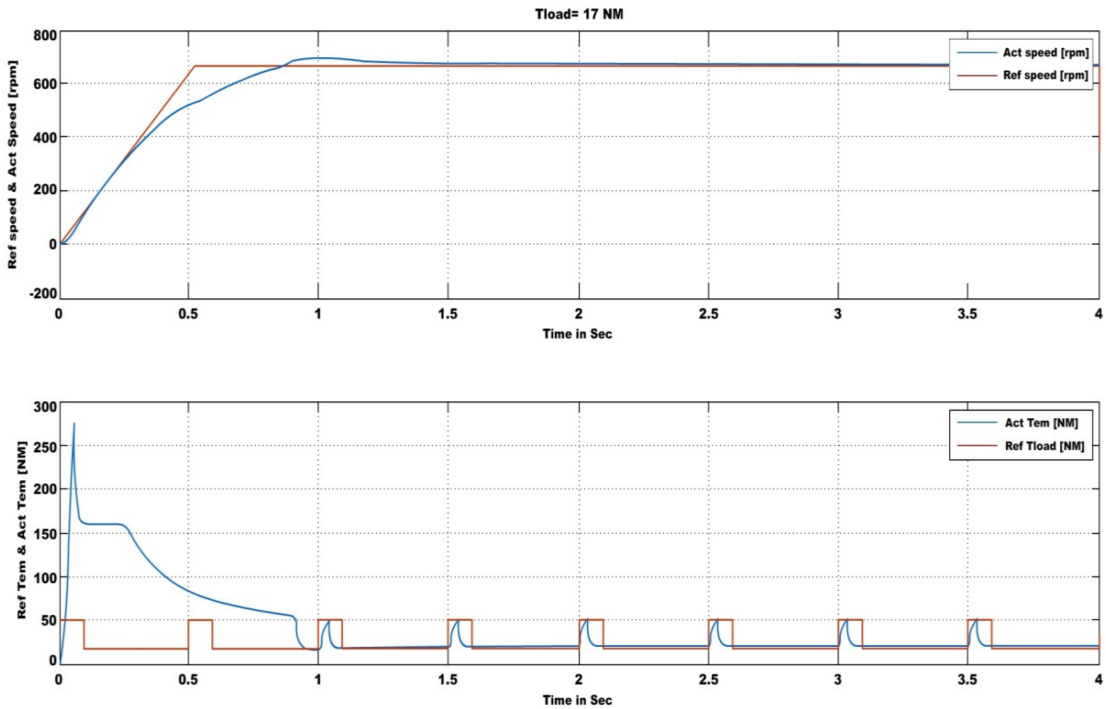

Fig. 11 Variation in time of rotation speed and torque of motor for 50% load torque when car moving on country road.

5. Conclusions:

- The Series DC Motor reaches steady state having constant rotation speed after transient period not exceeding 1.5 s in most loading cases of the car. This confirms that Series DC Motor is suitable to be used in electric cars and generally in electric traction.
- The maximum phase current in transient state is 370 A for less than 0.2 sec, when different load torques are applied and the maximum phase current in steady state is 45 A , which is less than nominal current.
- When load torque is increased or reduced to comply with country roads with holes and slopes, rotating speed is reduced or increased accordingly. The response of Series DC Motor is satisfactory.

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